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COMPLEX SMALL-SCALE STRUCTURE IN THE INFRARED EXTINCTION TOWARDS THE GALACTIC CENTRE

Andrew J. Gosling[1], Katherine M. Blundell[1] and Reba Bandyopadhyay[1]
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ABSTRACT

A high level of complex structure, or "granularity", has been observed in the distribution of infrared-obscuring material towards the Galactic Centre (GC), with a characteristic scale of $5'' - 15''$, corresponding to $0.2 - 0.6$ pc at a GC distance of 8.5 kpc. This structure has been observed in ISAAC images which have a resolution of $\sim 0.6''$, significantly higher than that of previous studies of the GC.

We have discovered granularity throughout the GC survey region, which covers an area of $1.6^\circ \times 0.8^\circ$ in longitude and latitude respectively (300 pc × 120 pc at 8.5 kpc) centred on Sgr A*. This granularity is variable over the whole region, with some areas exhibiting highly structured extinction in one or more wavebands and other areas displaying no structure and a uniform stellar distribution in all wavebands. The granularity does not appear to correspond to longitude, latitude or radial distance from Sgr A*. We find that regions exhibiting high granularity are strongly associated with high stellar reddening.

Subject headings: dust, extinction—Galaxy: center—infrared: stars—ISM: structure

1. INTRODUCTION

Observations towards the Galactic Centre (GC) are extremely difficult because of high levels of extinction from intervening material in the Galactic Plane. The gas and dust which form the inter-stellar medium (ISM), if distributed homogeneously along our line of sight, would produce ~ 100 magnitudes in visual extinction (Launhardt et al 2002), in stark contradiction to observations (e.g. Rieke & Lebofsky 1985; Catchpole et al 1990; Blum et al 1996; Dutra et al 2003) which indicate the true average extinction is $A_V \leq 30$. The explanation inferred for this, supported by numerous observations at different wavelengths (Catchpole et al 1990; Lis & Carlstrom 1994; Dutra et al 2003) is that the ISM towards the GC is distributed non-uniformly. Hitherto, no extinction map towards the GC has had an angular resolution $\leq 1'$.

We describe the results derived from new, high-resolution near-IR images of 26 fields within the nuclear bulge. These VLT-ISAAC fields (Bandyopadhyay et al. 2005), are 2.5×2.5 arcmin^2 in size, with a plate scale of $0.1484''$ per pixel. The fields are distributed throughout an area $1.6^\circ \times 0.8^\circ$ (l, b) centred on Sgr A*, avoiding areas of known high star formation. We obtained a limiting magnitude of $J = 23$ $(S/N = 5)$, $H = 21$ and $K_s = 20$ $(S/N = 10)$, taken on nights with seeing $\leq 0.6''$.

The purpose of this Letter is to report the discovery and quantify the size scales of structure in the dust distribution unresolvable in previous studies. A follow-up paper (Gosling et al. in prep.) presents extinction maps and a detailed analysis of comparisons with previous, lower-resolution maps such as that of 2MASS and DENIS.

2. GRANULARITY

Examination of the VLT-ISAAC fields of the GC reveals that the degree of reddening seen in colour-colour (C-C) and colour-magnitude (C-M) diagrams of the field populations varies widely (see Fig. 1b and e). This property is not evident in all fields. C-C plots for some of the fields (such as Fig. 1b) show two loci of stars, one for foreground stars, and another with reddening consistent with traditional values for the GC. C-C plots of other fields (such as Fig. 1e) show the locus of the non-local stellar population to be greatly extended along the reddening vector, and containing stars with reddening considerably in excess of the traditional GC reddening values.

Visual inspection shows that fields where the reddening appears to vary substantially within the field also display structure in the stellar distribution on sub-arcmin scales. This structure takes the form of filaments and clumpy regions within which the stellar density is dramatically reduced compared with the field average. We present evidence in §3.3 that these structures are related to the increased and varying reddening in these fields. The fine scale of the structures we have discovered were inaccessible to previous lower-resolution surveys such as 2MASS.

To quantify "granularity", we used statistical analyses to measure the structure of the observed stellar distribution as a function of wavelength. Wall & Jenkins (2003) present techniques for statistical analysis of 2-dimensional distributions of points. Their method is used to detect structure in galaxy distributions over the whole sky. To apply this test it is assumed that the underlying stellar distribution is random, and that the cause of the structure arises from the intervening extinction. The K_s-band images will be less affected by extinction than the J- and H-bands. If the underlying distribution of stars is random, then the K_s images should show a measure closer to random than equivalent images in J and H.

The test divides each field into a grid of cells, whose sizes were systematically varied from $150''$ to $1''$ to quantify the size scale of the structures. The mean star density per square arcsec was determined by dividing the number of stars in the entire field by the field area. The deviation of the number of stars observed in a grid cell was com-

[1] University of Oxford, Department of Physics, Keble Road, Oxford, OX1 3RH, U.K.

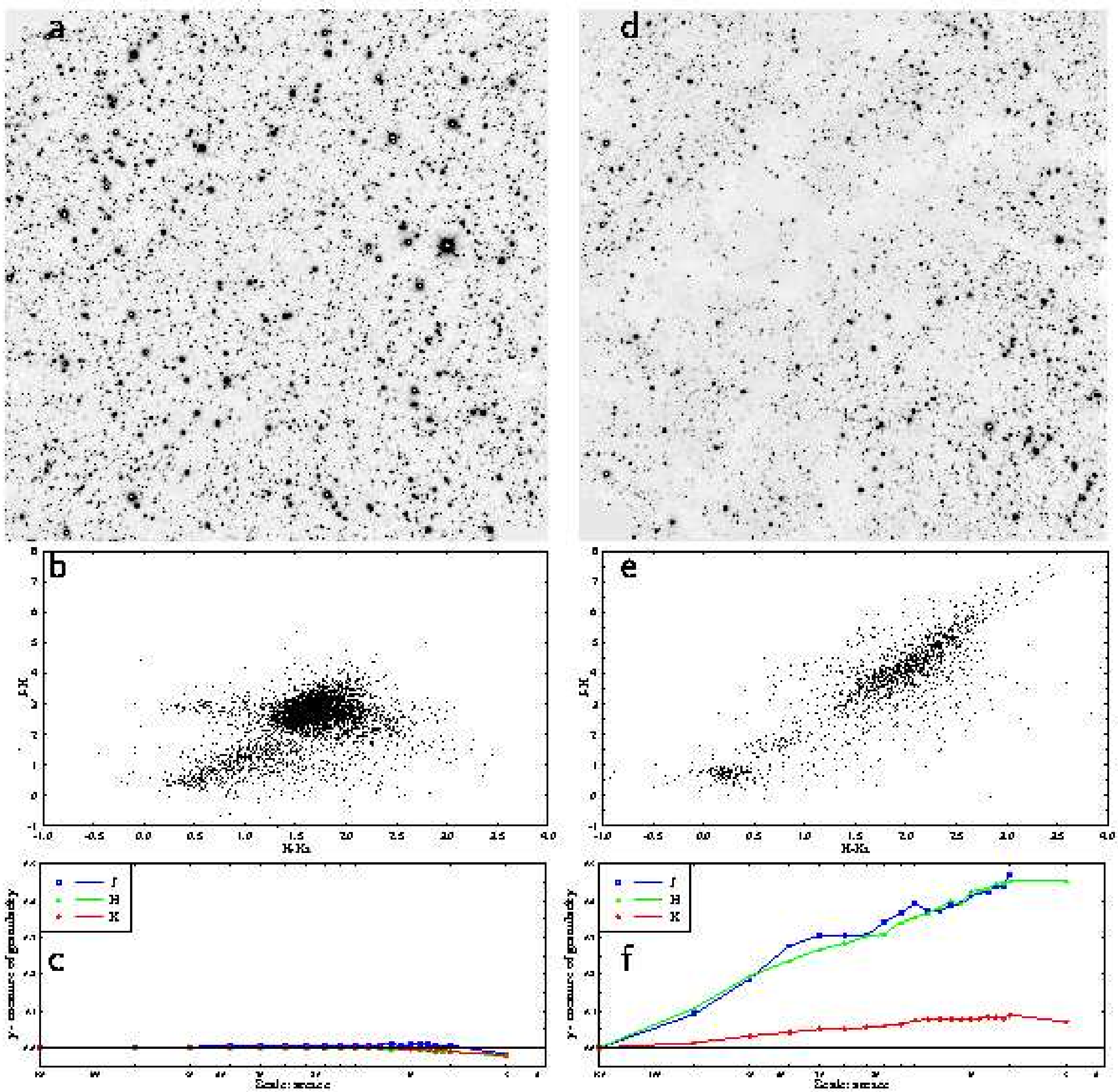

FIG. 1.— a) K_s image of a field with no apparent structure in the stellar distribution. b) C-C diagram of the stars in the field shown in (a). There are two main loci of stars: the local population to the bottom-left and the GC population in the centre. c) The measure of granularity for the field shown in (a). In all three bands it does not deviate from zero, as expected for a random distribution. d) K_s image of a field with obvious regions of low stellar density compared to the field average. e) C-C diagram for the field shown in (d). Note, compared to the C-C diagram in (b), the locus for the GC stars is extended to high reddening. f) The measure of granularity for the field shown in (d) shows that there is measurable structure in all three bands.

pared to the mean number per cell. The deviations from the mean were summed and the variance μ_2 of all of the cells was calculated. Because the mean number of stars per unit area is a constant, and it is the size of a cell that is altering, the variance is normalised to the size of the grid cell, as expressed in the formula below,

$$y = \frac{\mu_2 - \bar{n}}{\bar{n}^2} \qquad (1)$$

where y is the measure of the deviation from randomness for the whole field, i.e. granularity, and $\bar{n}$ is the expected number of stars in one grid cell.

The number of stars ranges from 1211 to 5592 in J images, 1792 to 6515 in H and 3005 to 9077 in K_s. To act as comparison data-sets, we produced 400 test fields with an equivalent spatial distribution to the observed fields using a computer random number generator to position points in a grid, 100 each with 1000, 3000, 5000 and 7000 points. We applied the same statistical test to these simulated fields as to the GC fields. Comparison of the simulated and actual data allowed us to determine whether the degree of

granularity measured in a GC field, y, was simply a result of low stellar density and as such a statistical effect, or the result of a non-random apparent stellar distribution. The maximum values of y for the random fields were 1.8, 0.08, 0.05 and 0.04 for the fields with 1000, 3000, 5000 and 7000 points respectively, at a scale of $2''$ (Fig. 2).

3. RESULTS

3.1. *Uniform Fields*

Of our 26 GC fields, 5 showed no measurable difference in granularity to the simulated random fields (Fig. 1 (left)). The stellar distribution of these fields is indistinguishable from random in all three wavebands indicating that the extincting material has no structure on scales measurable at the spatial resolution of our data. The C-C and C-M diagrams of these 5 fields indicate that there is a single value of reddening for these stars (consistent with an approximate value of $A_K = 2.5$ for the GC). This single value for the reddening agrees with the observed lack of granularity across these fields.

3.2. *Granular Fields*

The remaining 21 fields all exhibit some degree of structure in their stellar distribution and show a greater range of reddening in their stellar population than fields without granularity.

Ten fields show only a small level of granularity, with a maximum y value of 0.1 in J, reducing in H and showing zero granularity in $K_{\rm s}$. The C-C and C-M diagrams for these ten fields show reddening that is slightly increased and more varied than the fields with no granularity (§ 3.1) ranging over ~ 1 magnitude in $K_{\rm s}$.

The remaining 11 fields show granularity in all three bands. The granularity is highest in J, intermediate in H and lowest in $K_{\rm s}$; as expected the longer wavelength observations are less affected. Thus the $K_{\rm s}$-band images will have an apparent measured stellar distribution closer to the true underlying distribution. The C-C and C-M diagrams for these fields show a wide range of values of reddening within individual fields, with the values of reddening 2–3× that expected for the GC (see Fig. 1e).

3.3. *Granularity Properties*

The nature of the *wavelength dependence of the granularity*, namely highest y-values in J, intermediate in H and low/absent in $K_{\rm s}$, indicates it is an effect of intervening extincting material. Fig 1 demonstrates this relationship between extinction and the granularity in the stellar distribution. Further, the association of high and varied reddening in C-M and C-C diagrams with significant measured granularity (i.e. high value of y) provides independent evidence for the relationship between extinction and granularity. These data indicate that the cause of both observed effects is the same; namely, that both are a result of dust and gas structures in the GC. In Fig 3 we plot the range of the FWHM of A_K for each field versus their measured granularity, these values are given in Table 1 for all fields. The extinction values were calculated using the near infrared colour excess (NICE) method of Lada et al. (1994), with model giant branch colours supplied by P. Podsiadlowski (*priv comm*) for comparison. The extinction law of Rieke & Lebofsky (1985) was used to calculate extinction values from the colour excesses. A detailed spatial analysis of this relationship, including comparison to reference giant branches and analysis of the extinction law towards the GC, is presented in the follow up paper (Gosling et al.) together with extinction maps of the individual fields.

The characteristic scale for the size of the extincting regions is $5''-15''$ (Fig. 2), the same scale being measured in all three bands in all fields. This angular size corresponds to a physical scale of 0.2 pc − 0.6 pc at a GC distance of 8.5 kpc. The average separation of stars over all fields is $2.72''$ in J, $2.29''$ in H and $1.94''$ in $K_{\rm s}$. Fig. 2 shows that we can exclude the possibility that the observed granularity is due to the intrinsic stellar distribution at the 99.7% confidence level in all three bands. Note that the y parameter in Fig. 2 is truncated below the 3σ value of the average stellar separation.

Consideration of the granularity measure in all the fields with their positions on the sky showed that the granularity does not trace a field's position on the sky with respect to Sgr A*; no trend is seen with Galactic l, b, or projected radial distance from Sgr A*. In addition, there appears to be no relation between the stellar density of a field and its position with respect to Sgr A* or its level of granularity.

We investigated whether there was any clear link between the granularity and the extincting material observed in surveys at other wavebands. Comparison to ISOGAL MIR surveys (Omont et al 2003; van Loon et al 2003) did not show evidence that the granularity traced areas of strong MIR emission. A large number of structures observed in our study seemed to be narrow and elongated in appearance, so a comparison of the levels of granularity was made with non-thermal filaments and other features also observable in the radio (Vallée et al 2004; Yusef-Zadeh et al 2004; Mezger et al 1996). No correspondence of radio structure with levels of granularity was observed. The resolution of published IR extinction studies has been insufficient to allow comparison to the structures we have discovered in our high-resolution ($< 0.6''$) survey.

4. CONCLUSIONS

Complex structure in the extincting material towards the Galactic Centre has been observed and measured for the first time on arcsec scales. The angular scale of the structures is $5''-15''$ which corresponds to a physical scale of 0.2 pc − 0.6 pc at a GC distance of 8.5 kpc.

Granularity is only apparent in fields in which there is high and variable reddening, (derived from the observed stellar C-C and C-M diagrams). The granularity is likely to be the effect of extincting material obscuring the underlying stellar distribution. Granularity is higher in J, intermediate in H and low/absent in $K_{\rm s}$ as expected from the wavelength dependence of extinction. In 5 of the 26 fields where a single value of reddening for GC stars can account for the observed colours, no granularity is apparent.

We remark that the presence of extinction towards the GC on far smaller scales than previously observed, means that an average extinction correction may in many cases not be valid for photometry of individual stars in the nuclear bulge. Schultheis et al (1999) suggested that smaller-scale structures in the extinction distribution were respon-

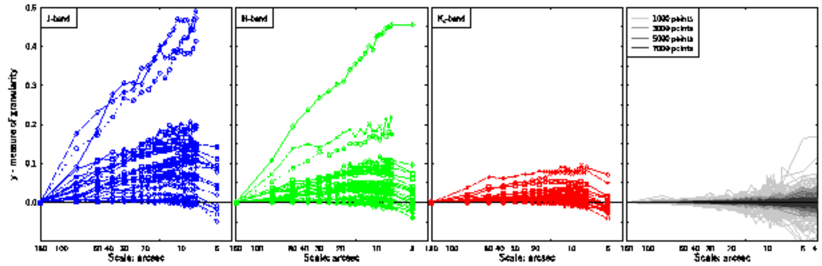

FIG. 2.— Statistical measures of the granularity y, in the GC fields. From left to right, these are for J, H, K_s-band observations. The rightmost panel is for test fields as described in the text; the darker colours in this panel represent the test fields with higher stellar densities. The granularity measured for our GC fields is truncated below 3-σ of the average stellar separation.

Field name	RA (J2000)	Dec (J2000)	Modal A_K	ΔA_K	y
2	266.76	-28.88		0.892	0.156
25	265.96	-29.16	2.765	0.446	0.011
35	266.05	-29.45		0.981	0.212
56	266.13	-29.31		1.605	0.490
58	266.19	-29.22		0.892	0.194
72	266.33	-29.09		0.981	0.167
83	266.11	-29.65		0.981	0.120
84	266.78	-28.82		1.070	0.108
89	266.69	-28.28		0.624	0.046
95	266.66	-28.93		0.713	0.074
130	266.52	-29.11		0.713	0.070
137	265.78	-29.40		0.892	0.203
151	266.24	-29.09		0.892	0.112
162	266.48	-28.34	2.052	0.624	0.005
174	267.13	-28.38		2.051	0.091
183	266.23	-29.32		0.892	0.076
195	266.41	-28.67	2.141	0.624	0.013
224	266.12	-28.94		1.160	0.417
243	266.10	-29.91	2.409	0.446	0.007
289	266.76	-28.24		0.802	0.086
312	266.39	-29.21		1.159	0.119
339	266.14	-28.74		0.713	0.148
391	265.55	-29.61	1.873	0.446	0.021
394	266.03	-29.45		1.159	0.490
423	266.30	-29.28		0.624	0.064
486	266.25	-29.00		0.802	0.144

ΔA_K is the FWHM of the extinction distribution (excluding the foreground x population). y is the maximum measured in the field. Values of modal A_K are only quoted for fields with negligible granularity for which an average A_K is meaningful.

sible for the observed double-peaks in histograms of stellar number versus A_V in the GC. The findings of this Letter strongly indicate that extinction may have significantly higher values on smaller scales than previously measured for the GC. A follow-up paper by Gosling et al., measures, maps and analyses the extinction at the GC.

A very recent paper by Nishiyama et al (2006) has found that IR extinction varies from sight-line to sight-line towards the GC and that the universality of IR extinction values are not valid for the GC region. Our paper demonstrates that the extinction varies on even finer scales than they suggest, in a way which correlates with the granularity of the stellar distribution in the GC.

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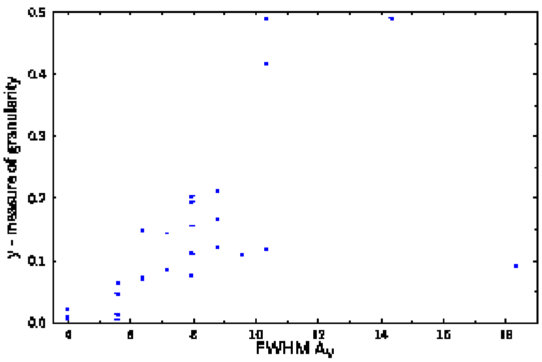

FIG. 3.— Relationship between level of granularity (y) in a field and the dispersion in the extinction distribution measured in the same field.

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